AD-A268 945

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0705-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE 103192	3. REPORT TYPE AND DATES COVERED FINAL REPORT 1/01/92-04/30/93

4. TITLE AND SUBTITLE

"Composites: Materials of the Future"

5. FUNDING NUMBERS

N00014-92-J-1652

DTIC ELECTE SEP 7 1993 S C D

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8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

OFFICE OF NAVAL RESEARCH
MATERIALS DIVISION
800 NORTH QUINCY STREET
ARLINGTON, VA 22217-5000

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12A. DISTRIBUTION/AVAILABILITY STATEMENT

DISTRIBUTION STATEMENT A
Approved for public release
Distribution Unlimited

12B. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

A diverse group from Europe and the U.S. were brought together to address broad aspects of composite systems, ranging from processing to design and including novel concepts. One objective was to compare and contrast approaches used for polymer-based systems with those for metal and ceramic systems. Another was to assess opportunities for new initiatives. A third was to explore concurrent engineering issues. Various generalizations can be made based on the presentations and discussions on the following: delamination and large scale bridging, remaining life, deformation and creep, crack growth micromeasurements, and novel approaches.

14. SUBJECT TERMS CONFERENCE, COMPOSITE MATERIALS	15. NUMBER OF PAGES 7
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	

93-19819

93 8 24 148

FINAL REPORT

Office of Naval Research

Contract No. N00014-92-J-1652

January 1, 1992 - April 30, 1993

MATERIALS

COMPOSITES: MATERIALS OF THE FUTURE

by

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WORKSHOP ON ADVANCED COMPOSITES

Held at

Schloss Ringberg, Germany
May 1992

Objectives

The intent of the workshop was to bring together a diverse group from Europe and the U.S., in order to address broad aspects of composite systems, ranging from processing to design and including novel concepts. One objective was to compare and contrast approaches used for polymer-based systems with those for metal and ceramic systems. Another was to assess opportunities for new initiatives. A third was to explore concurrent engineering issues.

The philosophy underlying the meeting states that the successful application of composite systems necessitates a much greater involvement of modelling, especially mechanism-based models, than has traditionally been the case in structural materials. The rationale for this belief concerns the large number of internal variables involved in composites (fiber, interfaces, matrices), as well as the relative complexity of the non-linear material responses, brought about by the differing intrinsic characteristics of the constituent materials. Consequently, an empirical approach to the qualification of the range of materials that best utilize the special characteristics of composites is prohibitively expensive. In the following summary, emphasis will thus be given to the status of research with regard to the role of modelling, especially mechanism-based, within a concurrent engineering framework.

The format of the meeting provided a unique opportunity for a diverse group to become acquainted with the breadth of issues relevant to advanced composite systems. The implications for future progress in the field await various interactions initiated as a result of the meeting. Nevertheless, various generalizations can be made, based on the presentations and discussions that occurred during the meeting.

Summary

i) Delamination and Large Scale Bridging

The polymer group emphasized aspects of delamination and remaining life: two of the critical problems in the structural utilization of polymer matrix composites (PMC), subject to either impact or fatigue loading. The information presented on delamination in PMCs, with typical lay-ups, indicated a helical pattern of delamination that reflects the relative fiber orientations in successive layers (D. Hull). While this behavior could be qualitatively understood, the complexity of the phenomenon led to the suggestion that simple mechanism-based relationships are unlikely, either between the imposed force and the delamination dimension or the delamination size and compressive strength. This is an area that would appear to derive benefit from a strong mechanics input, based on the careful observations now available, coupled with established delamination crack growth characterization.

A reasonably comprehensive measurement and analysis capability for delamination crack growth now exists (J. G. Williams and A. Kinlock). Data are available for a range of mode mixities and materials, which indicate that mode II crack growth is suppressed by fracture surface roughness and associated asperity contacts. This roughness is, in turn, related to the mode I mechanism of crack advance operating at the actual crack front, as also found in CMCs, in rocks and at interfaces. However, the mechanics used to represent this behavior ignore the effects occurring near the crack front: instead, a 'global' energy analysis has been developed. Implicit in this approach is the existence of a process zone subject to crack surface tractions, caused either by roughness or bridging fibers, whereupon the effects occurring at the crack front are considered irrelevant. This philosophy is somewhat analogous to that used in Large Scale Bridging Mechanics (LSBM). However, the LSBM concept is more rigorous. It invokes a traction law that characterizes the behavior within the process zone. LSBM solutions presented for two different problems illustrated the approach. One application was concerned with the effects of holes and notches on the tensile properties of CMCs (Suo). The other referred to crack growth along a metal/ceramic interface with ductile ligaments providing the tractions (Tvergaard). A broad development of LSBM and its application to a variety of problems in advanced materials is recommended. This approach may be mechanism-based and have wide engineering utility.

ii) Remaining Life

The activities concerned with remaining fatigue life demonstrated considerable commonality between materials: PMCs (Reifsnider), MMCs (Johnson, Ritchie) and CMCs (Ritchie). There were also connections to the stochastics of fiber failure within a composite (Curtin). The basic philosophy is that fatigue degrades the matrix and sheds load onto the fibers. When the ensuing failure probability of the fibers reaches a critical level, at the appropriate in-situ gauge length, the composite fails. However, the characterization of load shedding has been based on empirical parameters (such as the Smith-Watson-Topper formula), with no distinction made between cyclic plasticity, matrix cracking, etc. <u>The potential exists to use mechanism-based models of these matrix phenomena, coupled with a rigorous stochastics of fiber failure, in order to generate lifing models.</u>

iii) Deformation and Creep

Analysis of the behavior of composites subject to either time-dependent or time-independent deformation indicated crucial influences of both fiber failure and interface debonding (McMeeking, Leckie). Strong anisotropy also exists. Mechanism-based models of these behaviors are well advanced, with some validation achieved in Ti and Al matrix composites. <u>Additional experimental work that explicitly addresses these models is considered important, especially at elevated temperatures.</u> The modelling of effects of dispersoids on matrix creep, including the creep threshold, also appear to be well advanced (Arzt), with good experimental corroboration. <u>An interesting opportunity appears to involve the coupling of the dispersoid strengthening results with those for fiber strengthening, in order to identify regimes for exploiting both mechanisms in a synergistic manner.</u>

iv) Crack Growth

Crack growth in biphasic materials was addressed in a relatively comprehensive manner for polymers, ceramics and cermets (hard metals). The resistance enhancement was addressed as a coupling between the non-linear deformation of <u>ligaments</u> and non-linearity within a <u>process zone</u>. For metal/ceramic systems, models and experiments concerning the partitioning of the plastic dissipation between the metal ligaments and the process zone (Fishmeister, Tvergaard) verified that partitioning occurs. Moreover, the ratio of ligament to process zone dissipation was predicted to be sensitive to constituent

properties. The experimental assessment of process zone dissipation, involving either plasticity or microcracking (Faber), has also progressed well, with a growing correlation between modelling and experiment. Further rigor should be provided upon using combined ligament/process zone models of the type presented by Tvergaard.

Ligament characterization subject to cyclic loading (Ritchie, Rödel), revealed the concern that degradation usually occurs. The degradation is gradual when friction dominates, such as in large grained ceramics and Ti MMCs (Marshall). However, metal ligaments often experience rapid fatigue failure, because of the magnified strain amplitude that occurs between the crack faces. Although, the degradation can be minimized by interface debonding (Evans). Nevertheless, fatigue susceptibility is inevitable and presents a limitation on the use of materials that rely on inelastic ligaments for enhanced toughness. Fortunately, this problem does not arise in materials with elastic ligaments, such as bridging fibers in CMCs and certain MMCs.

For the polymer systems, the corresponding ligament phenomenon is associated with crazes. The invention here (Argon) was the use of a dispersed fluid phase that softens the craze ligaments when intercepted by a crack. This softening encourages distributed crazing which, in turn, enhances the ductility and overall toughness of the material.

A commonality of ligament effects is emerging, within the framework of LSBM. This mechanics, combined with careful measurements, is leading to a rigorous understanding of traction laws, having a wide spectrum of applicability.

v) Micromeasurements

A mechanism-based approach for characterizing performance and for implementing in design requires a methodology for measuring various constituent properties. Among the most critical are interface responses in composites, residual stresses and in-situ fiber properties. A presentation on this topic (Marshall) indicated that a spectrum of imaginative techniques have been devised and used on CMCs, MMCs and IMCs. While the techniques require specialized equipment, the measurements are now straightforward and the mechanics needed to deconvolute the data rigorously derived. Implementation of these methods on a generalized basis is expected to have a major role in the development and use of models for fatigue, fracture, etc.

vi) Novel Approaches

A series of presentations established that layered material concepts are exciting and a rich field for future research. Some of the principles that govern the structural characteristics of natural materials, such as shelis and wood (Heuer), have been utilized to produce layered systems comprising SiC/C (Kendall), oxide/oxide (Lange), ceramic/metal and intermetallic/metal (Evans). The interactions of propagating cracks with the layers, through debonding, combined with the lateral spreading of either plasticity or phase transformations, have been identified and shown to be beneficial. A modelling effort has been initiated, but much remains to be done. A strong activity in this area could be expected to provide important new opportunities, given the inherent advantages of layered systems (over fiber composites) in both manufacturing flexibility and component design.

Hybrid systems were also described. One system consisted of metal cylinders within an intermetallic matrix (Nardonne). This system exhibited excellent properties, particularly when the interfaces were treated in a manner that enhanced debonding. Another system comprised a hybrid of thin ceramic layers with fiber reinforced layers (Lange). This system also combined good properties with manufacturing flexibility.